Auditory Effects of Mid-Frequency Sonars on Marine Mammals

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Award Number: N0001407WX20377
http://www.spawar.navy.mil/sandiego/technology/mammals/

LONG-TERM GOALS

The long terms goals of this effort are to develop mathematical models to predict the auditory effects of mid-frequency tones, similar to those emitted by Navy tactical sonars, on marine mammals. The models would be used in acoustic effects analyses in environmental documents and to develop appropriate mitigation procedures.

OBJECTIVES

The objectives for FY07 were (1) to measure temporary threshold shift (TTS) in a bottlenose dolphin exposed to intermittent tones using both auditory evoked potential (AEP) and behavioral methods and (2) to evaluate the suitability of terrestrial mammal TTS models to fit the bottlenose dolphin TTS data. Prior effort established the growth and recovery of TTS after single, continuous exposures. The focus for FY07 was to examine the effects of multiple exposures and develop the capability of using AEP measurements for TTS.

APPROACH

Auditory effects are assessed by measuring the amount of TTS, defined as the difference between hearing thresholds measured before and after an intense sound exposure. Hearing thresholds were measured using either a behavioral response paradigm, where the subject is trained to perform a specific action when it hears a test tone, or an electrophysiological method, where AEPs in response to test tones are measured.

Behavioral methods developed at SSC San Diego allow thresholds to be obtained within four minutes of intense sound exposures. This is accomplished using computer-controlled stimulus presentations, multiple trials before subject reinforcement, and an acoustic response by the subject. Dolphins typically produce an acoustic response (a whistle) within a few hundred milliseconds of tone onset, allowing a rapid pace of stimulus presentation and fast threshold estimates. A modified up/down descending staircase technique was used to adjust the stimulus level in an adaptive fashion from one trial to the next and bracket the threshold.

Electrophysiological thresholds were estimated by measuring a type of AEP called the auditory steady state response (ASSR). Hearing tests were conducted underwater using a direct field stimulus (not a “jawphone” stimulus). A statistical test (magnitude-squared coherence) was used to objectively

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Auditory Effects of Mid-Frequency Sonars on Marine Mammals**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Space and Naval Warfare Systems Center,Biosciences Division, Code 2351,53560 Hull Street,San Diego,CA,92152**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

determine the presence or absence of AEPs in response to stimuli at different levels. Thresholds were based on the lowest detectable response with a 1% probability of false detection.

The subject was trained to wear suction cup-mounted hydrophones during the fatiguing sound exposures to allow estimates of the received sound levels regardless of subject location. Exposures were characterized by the average sound pressure level (SPL), sound exposure level (SEL), and exposure duration. Tests were conducted in a quiet, above ground test pool.

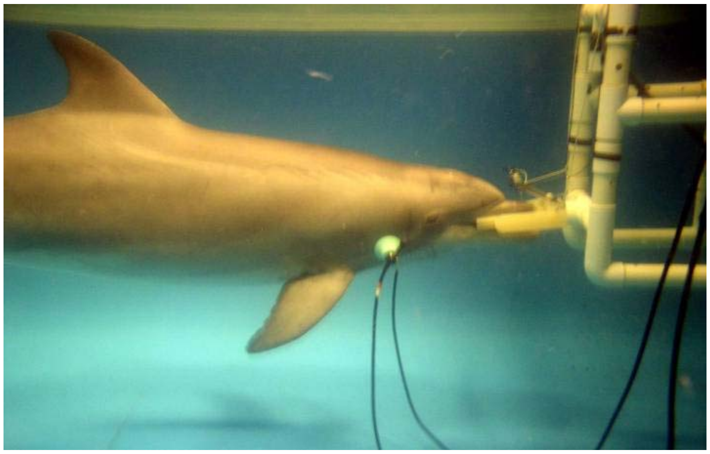

Figure 1. The dolphin subject in the pool during a hearing test. Suction cup-mounted hydrophones placed near the ears were used to record the sound levels during the exposure.

James Finneran served as the PI and project manager, developed the hardware and software AEP and behavioral hearing test systems, analyzed the acoustic and threshold data, and performed the TTS mathematical modeling. Carolyn Melka served as the technical coordinator for the behavioral and AEP testing in the pool, conducted the daily experiments, calibrated the sound system, and analyzed/archived the resulting data. Dorian Houser collaborated on AEP testing and benchmarking AEP data versus behavioral data. Brian Branstetter assisted with data collection and analysis.

WORK COMPLETED

Previous years (FY05-06) established the growth and recovery of TTS in a dolphin after single continuous exposures. In FY07, we trained a second dolphin for behavioral testing in our quiet test pool, then measured (and compared) AEP and behavioral data for both tests subjects. Our portable AEP system was modified to permit multiple ASSR testing (testing hearing at multiple frequencies simultaneously), which we did during baseline and TTS measurements. We finished TTS measurements at 3 kHz using intermittent tones with 50% duty cycle and TTS measurements at 3 and 20 kHz using intermittent tones with 6% duty cycle (representative of tactical sonars). We also compared behavioral and AEP TTS measurements following the same exposure to determine if the two methods produced the same results. Finally, a mathematical model was developed to predict TTS4 (TTS 4 min after exposure) as a function of exposure SPL and duration.

RESULTS

Comparisons between AEP and behavioral data collected in the quiet pool confirmed that AEP thresholds are similar to behavioral thresholds and that AEP-derived audiograms reflect the shape and upper cutoff frequency of the behavioral audiogram.

Multiple ASSR measurements before and after exposure to single 20 kHz tones revealed the frequency spread of TTS, with the maximum shift occurring close to 1/2-octave above the fatiguing sound exposure (Fig. 2). It is significant that the narrowband exposure (a 20 kHz tone) produced a large bandwidth TTS, which extended from 15-20 kHz to 40-50 kHz, and that the largest TTS did not occur at the exposure frequency, but at a higher frequency. The use of the multiple ASSR technique in these measurements is noteworthy because it is the first time this technique has been used to measure TTS in any mammal (terrestrial or marine). The 20 kHz TTS data also revealed larger amounts of TTS than observed after 3 kHz exposures with the same duration and SPL, suggesting that the onset of TTS is lower or the TTS growth rate is steeper at 20 kHz compared to 3 kHz; i.e., the 3 kHz TTS data may not be suitable for predictions at higher frequencies where dolphins have more sensitive hearing.

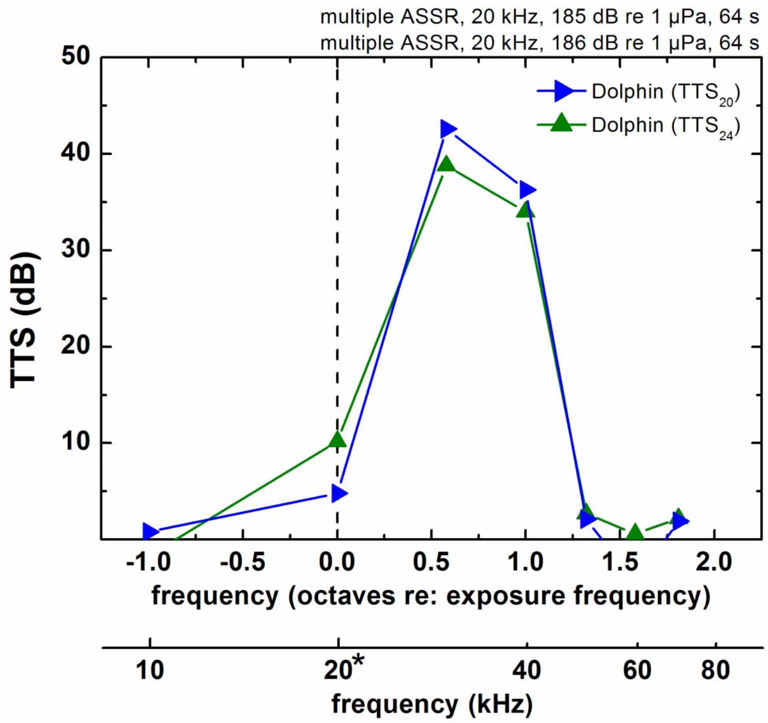

Figure 2. TTS as a function of frequency after a 20 kHz exposure. The largest TTS (about 40 dB) occurred at 30 kHz, close to 1/2-octave above the exposure frequency. The next largest TTS (~35 dB) occurred at 40 kHz, followed by 20 kHz (~5-10 dB). Thresholds at 10, 50, 60, and 70 kHz were not affected.

Behavioral and ASSR measurements made after the same exposure revealed that the amount of TTS measured with steady-state evoked potentials was always larger, sometimes dramatically larger (Fig. 3), where the behavioral measure was around 20 dB and the ASSR TTS was about 45 dB. This raises questions regarding the nature of this difference — if it occurs at smaller amounts of TTS and the applicability of pooling behavioral and TTS data. It also raises the question of whether steady-state evoked potential measurements are a more sensitive indicator of the auditory effects of noise compared to behavioral effects; i.e., there may be measurable changes in the ASSR after the behavioral thresholds are no longer distinguishable from the pre-exposure values. More effort is needed to understand the relationships between the behavioral and ASSR measures and how they are affected by noise.

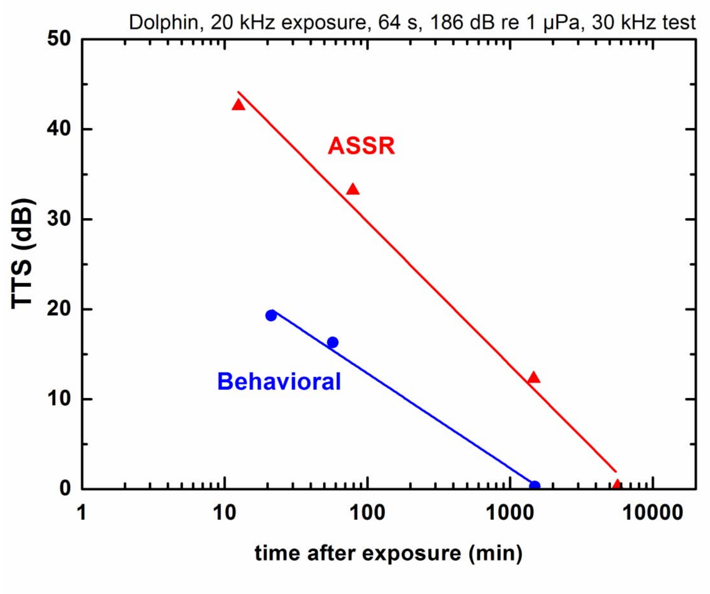

Figure 3. The amount of TTS measured with the ASSR was always larger than that measured behaviorally, for example TTS15 of 45 dB for the ASSR compared to 20 dB measured behaviorally. In both cases TTS recovery was a logarithmic function of time.

The TTS results from multiple exposures (e.g., Fig. 4) revealed that when exposures are sufficiently close in time, an accumulation of TTS can occur, where the magnitude of the TTS steadily increases with each exposure. The manner in which this accumulation occurs depends on the duty cycle, duration of the exposure and the amount of shift produced from a single event. Figure 4 shows that the TTS from four 16-s tones is larger than that from a single 16-s tone – there is an accumulation of TTS over multiple exposures. However, the overall TTS is less than that from a single 64-s exposure – there is still some amount of recovery in the quiet intervals between exposures. The concept of “equal energy” means that exposures with equal energy produce equal effects, regardless of how that energy is distributed in time. We have assumed that this over-estimates the effects of intermittent exposures, since some amount of recovery would probably occur in the quiet period between pulses. Our intermittent TTS data now demonstrate that some recovery does occur, and therefore the manner in which Navy accumulates energy for estimates of TTS in environmental documents (using equal energy) is a protective technique, since it over-estimates the effects for intermittent exposures like tactical sonars.

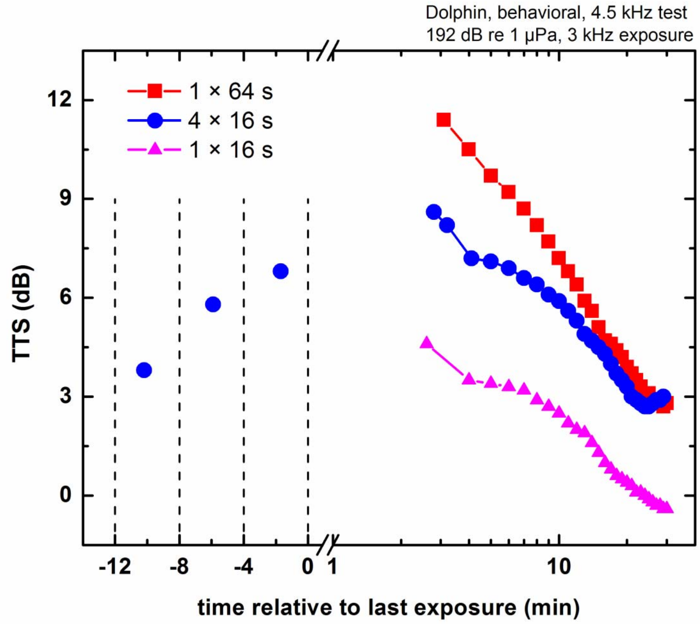

Figure 4. The amount of TTS induced by multiple (intermittent) exposures was larger than that produced from a single exposure with the same SPL and duration, but less than that produced from a single exposure with the same total energy

The limited range of data (e.g., no asymptotic threshold shift data) prevented the application of existing terrestrial mammal TTS models to the data obtained from the dolphin subjects; however, the dolphin data was fit nicely with a 2-D function of SPL and duration defined by:

$$TTS_4 = m_1 \log_{10}\left(1+10^{(SPL-m_2)/10}\right)\log_{10}\left(1+10^{(D-m_3)/10}\right), \qquad (1)$$

where D is the exposure duration and m1, m2, and m3 are fit parameters. Least squares fit values were m1 = 0.7833, m2 = 171.4, and m3 = -10.14. This function can be used to predict the amount of TTS4 for ~3 kHz exposures with arbitrary SPL and duration over the range of the underlying data: from $1 \leq D \leq 128$ seconds and $100 \leq SPL \leq 200$ dB re 1 μPa. Throughout this range, the data are represented well (R = 0.867) by this function (Fig. 5), which means that Eq. (1) can be used in Navy acoustic analyses to predict the effects of tactical sonars when the cumulative exposure duration is between one and 128 seconds.

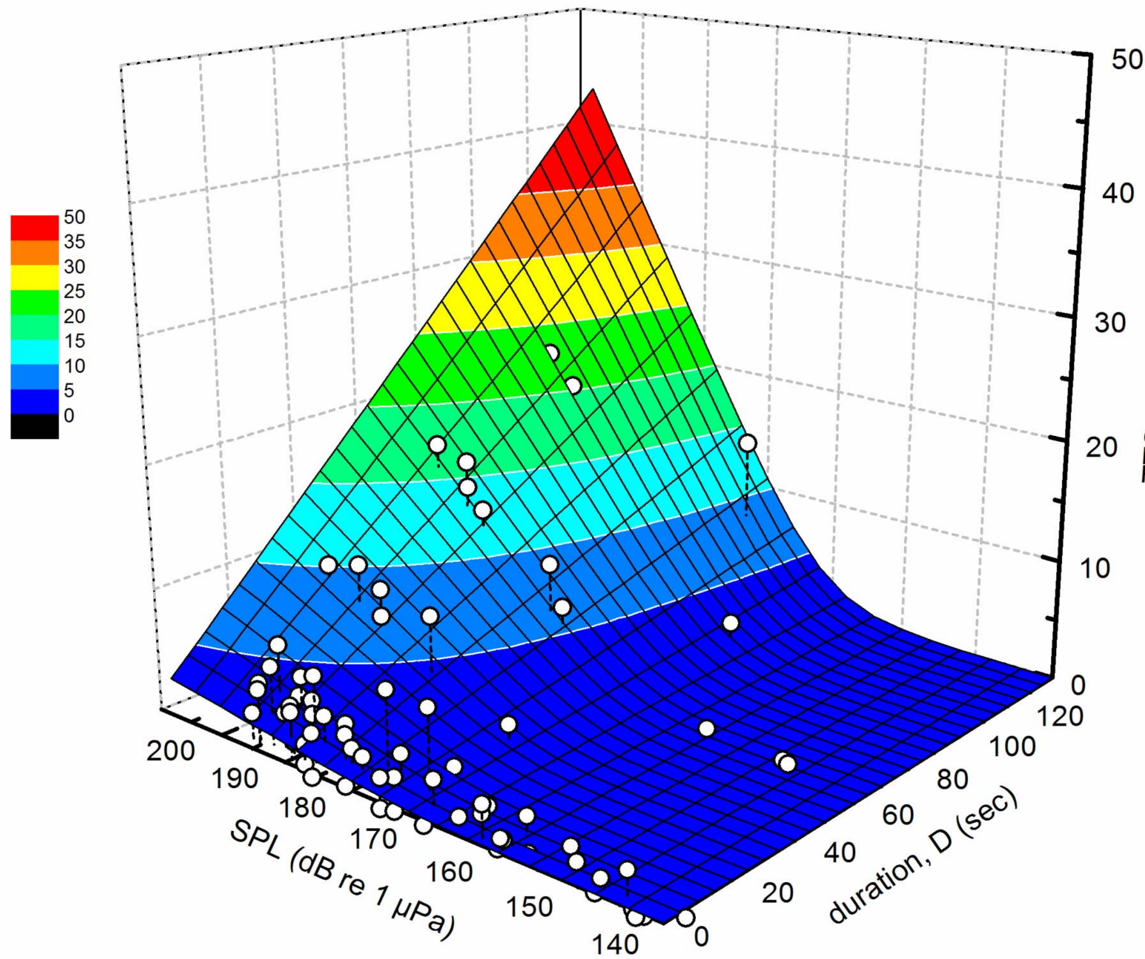

Figure 5. TTS mathematical model results presented as a three-dimensional surface that is a function of SPL and exposure duration.

IMPACT/APPLICATIONS

The model for TTS as a function of SPL and duration is suitable for use in Navy environmental analyses for predicting the effects of mid-frequency tactical sonars on marine mammals. The model properly captures the manner in which the amount of TTS deviates from the equal energy approximation as the exposure duration increases. The model can also be used to predict the effects of intermittent exposures, provided that the "effective" SPL is based on the total cumulative sound exposure level and the cumulative ping duration. This will provide a conservative (i.e., protective) approach, since the intermittent TTS data showed that there is some small recovery between pings with duty cycles of 6%.

The differences observed between the ASSR and behavioral TTS may have a profound impact on the way the TTS data are collected and analyzed in the future. At present, ASSR data are combined with behavioral data to develop predictive models; however, the comparison data suggest that there may be fundamental differences in these data, that they should not be pooled, and that ASSR measures are more sensitive to the effects of sound. The differences between observed TTS at 3 and 20 kHz suggest that the onset of TTS is lower or the TTS growth rate is steeper at 20 kHz compared to 3 kHz. This means that the 3 kHz TTS data may not be suitable for predictions at higher frequencies were dolphins have more sensitive hearing, necessitating collecting additional data for accurate predictions at higher frequencies.

TRANSITIONS

Data resulting from this project have been presented at scientific conferences, MMC FACA meetings, transmitted to ONR, NMFS, and CNO N45, and published in peer-reviewed scientific journals. These data are often used in environmental assessments and impact statements that must be prepared for weapons systems development, surveillance systems development, quality assurance tests, oceanographic research, and training exercises. The TTS data that have been collected to date have been used extensively by Navy environmental analysts and have been used to derive acoustic impact criteria for various EA and EISs, including the SEAWOLF Shock Trial, the WINSTON CHURCHILL Shock Trial, LPD 19 Shock Trial, USWTR, HRC, SOCAL, and AFAST EISs. These data have also informed decision making on naval exercises such as RIMPAC and provided the basis for deconfliction guidelines for US Navy Marine Mammal Systems operating near active acoustic sources. The TTS data are used by not only the US Navy, but also by various NATO allies and the seismic industry for predicting and mitigating effects of sonars and explosives on marine mammals.

The AEP system software we developed (called EVREST — the Evoked Response Study Tool) has been shared with other researchers conducting AEP measurements, including those at Long Marine Lab at UC Santa Cruz, the Hawaii Institute of Marine Biology, and the Pennsylvania State University Applied Research Lab.

RELATED PROJECTS

None

PUBLICATIONS

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